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Predicting the production rates of cosmogenic nuclides

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Abstract

The determination and some uses of production rates of cosmogenic nuclides are reviewed. Emphasis is on work done since 1993 for long-lived cosmogenic radionuclides in extraterrestrial matter. Several Monte Carlo computer codes are being used to numerically simulate the interactions and transport of cosmic-ray particles. Thin- and thick-target irradiations have been done with protons to determine reaction cross sections and to experimentally simulate cosmic-ray bombardments. Cross sections for some neutron-induced reactions are being measured or inferred from thick-target irradiations. Some other work involving cosmogenic-nuclide production rates are discussed.

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1. Introduction

Production rates of the nuclides made in matter by cosmic-ray particles are needed to interpret measurements of these cosmogenic nuclides. These nuclides can be used to determine the length of time that the object was exposed to cosmic-ray particles and other aspects of its exposure history, such as erosion rates of terrestrial rocks. For lunar samples and a few meteorites, we need production rates for both high-energy (~1-10 GeV) galactic-cosmic-ray (GCR) particles and lower-energy (~10-100 MeV) solar energetic particles [e.g., 1]. Production rates are needed for a variety of compositions and irradiation geometries. As new radionuclides become routinely measurable, such as ^{60}Fe, their production rates need to be determined.

As often several cosmogenic nuclides are measured in a sample, the production rates for those nuclides need to be consistent among themselves. For example, several cosmogenic nuclides are needed to unfold the three parts of the exposure records of some lunar meteorites: exposure at some depth in the Moon, irradiation as a small object of a given size in space, and the terrestrial age (the length of time that the meteorite was shielded from cosmic rays on the Earth's surface).

In 1987 for the 4th International Symposium on Accelerator Mass Spectrometry (AMS), I reviewed the ability to predict production rates of cosmogenic nuclides [2]. Much has changed since then, such as the much greater use of terrestrial in-situ-produced cosmogenic nuclides and the utilization of Monte Carlo production/transport codes to numerically simulate the cosmic-ray-particle interactions that make nuclides. There are also many more measured proton-induced cross sections for producing cosmogenic nuclides, and thick- and thin-target irradiations are being used to determine cross sections for neutron-induced reactions. After briefly mentioning work on determining production rates for terrestrial in-situ cosmogenic nuclides, recent work (mainly since 1993) on extraterrestrial cosmogenic long-lived radionuclides will be presented. For a review of work up through 1993 on cosmogenic nuclides in extraterrestrial matter, see [3].

2. Terrestrial In-Situ Cosmogenic Nuclides

The use of AMS to measure in-situ-produced cosmogenic radionuclides in terrestrial surfaces has grown very rapidly with many applications. Many measurements and models have yielded fairly-good production rates for these nuclides [e.g., 4]. Work is continuing on expanding the list of nuclides used, on developing the ability to use additional minerals and compositions, and on using natural and artificial samples to determine better production rates [e.g., 5]. Efforts [e.g., 6] are being made to understand the contributions of muons to the production of terrestrial cosmogenic nuclides, especially at depths below a few meters where muon production becomes important. Numerical simulations [e.g., 7] are being done for the production and transport of cosmic-ray particles to the Earth's surface and the subsequent production of nuclides in the atmosphere and surface. Improved transport and production calculations using better physical parameters for cosmic-ray interactions above ~10 GeV were recently done for the Earth's atmosphere [8]. Some work on production rates of terrestrial cosmogenic nuclides will be presented in this volume of papers from AMS-8.

3. Numerical Simulations

Much work has been done on using Monte Carlo codes to numerically simulate the interactions of cosmic-ray particles that produce cosmogenic nuclides in extraterrestrial matter [e.g., 9,10]. The results using the fluxes calculated by these codes are reproducing the measurements well and allow measured production rates to be extended to new planetary objects, unusual irradiation geometries, different bulk compositions, and additional target elements. The production of cosmogenic nuclides made by spallation reactions with various threshold energies from a few MeV to ~100 MeV and by neutron-capture reactions have been numerically simulated.

Calculations using the LAHET Code System (LCS) have been done for spallogenic nuclides such as ^{10}Be, ^{26}Al, and ^{36}Cl in lunar samples and meteorites. The calculated production rates agree well with measured concentrations of cosmogenic nuclides in documented lunar samples [e.g., 11] and meteorites such as Knyahinya with known pre-atmospheric size and sample locations [12,13]. Effective fluxes of GCR particles were determined from these comparisons [e.g., 12]. The calculated production rates as a function of depth in a 15-meter iron meteoroid were used to model measured concentrations of ^{10}Be, ^{26}Al, and ^{36}Cl in samples of Canyon Diablo [14]. A similar computer code, HERMES, has also been used to calculate production rates of spallogenic nuclides in meteorites [9,15,16].

The LCS code has been use to calculate rates for the capture of neutrons near thermal energies by several isotopes. Calculated concentrations of ^{41}Ca made by neutron-capture reactions with ^{40}Ca in a lunar core agreed well with measurements [17]. Concentrations of ^{59}Ni in meteorite fragments and in small spheroids from the Canyon Diablo iron meteoroid were used to determine the depth of these samples in the pre-atmospheric body [18]. Hydrocodes modeling the impact of this body with the Earth and the sample depths determined from ^{59}Ni were used to infer the impact velocity of the Canyon Diablo meteoroid [18].

4. Cross-Section Measurements

Many cross sections have recently been measured using protons for the production of ^{14}C [11,19], ^{10}Be and ^{26}Al [20-22], ^{36}Cl [23,24], and other nuclides [e.g., 25]. These and existing proton cross sections have allowed good unfolding of measured profiles of solar-proton-produced nuclides in lunar samples to infer average fluxes of solar protons in the past using ^{10}Be and ^{26}Al [26,27], ^{36}Cl [28], and ^{41}Ca [26]. The fluxes of protons with energies above 30 and 60 MeV are better determined than the fluxes above 10 MeV or the spectral shape of these protons [29]. These results suggest that the fluxes of solar protons ~1 million-years ago were lower than those more recently [29].

For reactions induced by galactic-cosmic-ray particles, one needs cross sections for both high-energy protons and for energetic neutrons [e.g., 16]. Some work is being done to measure cross sections for ^{14}C and several other radionuclides using quasi-monoenergetic 80- and 120-MeV neutrons and "white" neutrons with energies of ~3-750 MeV [19]. Cross sections for neutrons with energies up to 90 MeV for making ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl will soon be reported [M. Imamura and K. Nishiizumi, priv. comm., 1999]. Other facilities to measure neutron-induced cross sections are being developed [e.g., 30].

5. Thick-Target Irradiations

There has been work on understanding production of cosmogenic nuclides by GCR particles (mainly neutrons) using nuclides measured in spherical thick targets of iron or stony material isotropically bombarded by high-energy (0.6- and 1.5-GeV) protons [9,16]. Depth-versus-concentrations profiles have been measured for nuclides in foils of various pure elements or compounds. Work is in progress to use HERMES calculations and the measurements from these thick targets or from extraterrestrial samples to infer neutron cross sections [e.g., 31]. Such cross sections will be used with the particle fluxes from particle production/transport codes like HERMES to calculate production rates of cosmogenic nuclides.

6. Other work on production rates

M. Honda has extended his two-parameter model for the production rates of spallogenic nuclides [32] to additional nuclides [33]. Cosmogenic radionuclides have been measured in meteorites with short exposure ages, as determined from low concentrations of cosmogenic ^{21}Ne [34]. Such meteorites have been used to infer production rates of cosmogenic nuclides. However, many of these meteorites have had complex exposure irradiation histories, which means that production rates can not be inferred from these meteorites.

Some work has been done on studies of cosmogenic-nuclide production in iron meteorites. Some of these iron meteorites were very large objects (radii of many meters) in space [14,35]. Measurements of long-lived radionuclides in iron meteorites have confirmed earlier work indicating that the fluxes of GCR particles during the last 10 million years (Ma) are higher than those for the past 150-700 Ma [36].

7. Discussion

The use of codes that numerically simulate cosmic-ray interactions, such as LCS [7,10], HERMES [9,16], and GEANT [8], has resulted in improved production rates for a wide range of cosmogenic nuclides. These codes can handle all irradiation geometries and compositions, with the main limitation being the lack of cross sections for making some nuclides from certain target elements. Most other methods for determining production rates were developed for extraterrestrial matter and do not work well for unusual sizes, shapes, and compositions.

Work needs to be done on better understanding how good are these calculated production rates (believed to be good to ~10% for commonly-studied nuclides) and where are the sources of errors in these calculations. Comparisons among codes are needed to check the calculated fluxes of cosmic-ray particles. Good experimentally-determined cross sections for neutron-induced reactions will help to test these code-calculated particle fluxes and will result in better production rates.

Much work will be done during the next few years on testing and extending these codes, in obtaining and using better cross sections, and in comparing calculated production rates with a wide range of measurements. These codes and associated nuclear databases will give better production rates and will also be used for new cosmogenic nuclides and irradiated materials.

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